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SHIELDING THE POWER GRID FOR TOMORROW

# Droop-Control-Aided State Estimation in Active Distribution Systems

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# Introduction – 1

**Background**

- DRESs ➔ **Increased** operational complexity of distribution grids
- Growing necessity for continuous **monitoring**
- **State estimation** as the main facilitator

- Main **attributes** of state estimation techniques:
  - Measurement noise removal
  - Bad data detection
  - Deliberately injected false data (**cybersecurity** breach)

# Introduction – 2

**State-of-the-art**

**Our Focus**

- Main DSSE categories: **Model-free** & **Model-based**

**Machine learning** **Robust optimization**

- Several **variants** of model-based solutions exist aiming to improve
  - calculation performance
  - solution accuracy
- Common **drawback** ➔ Local control logic of DRESs is **neglected**

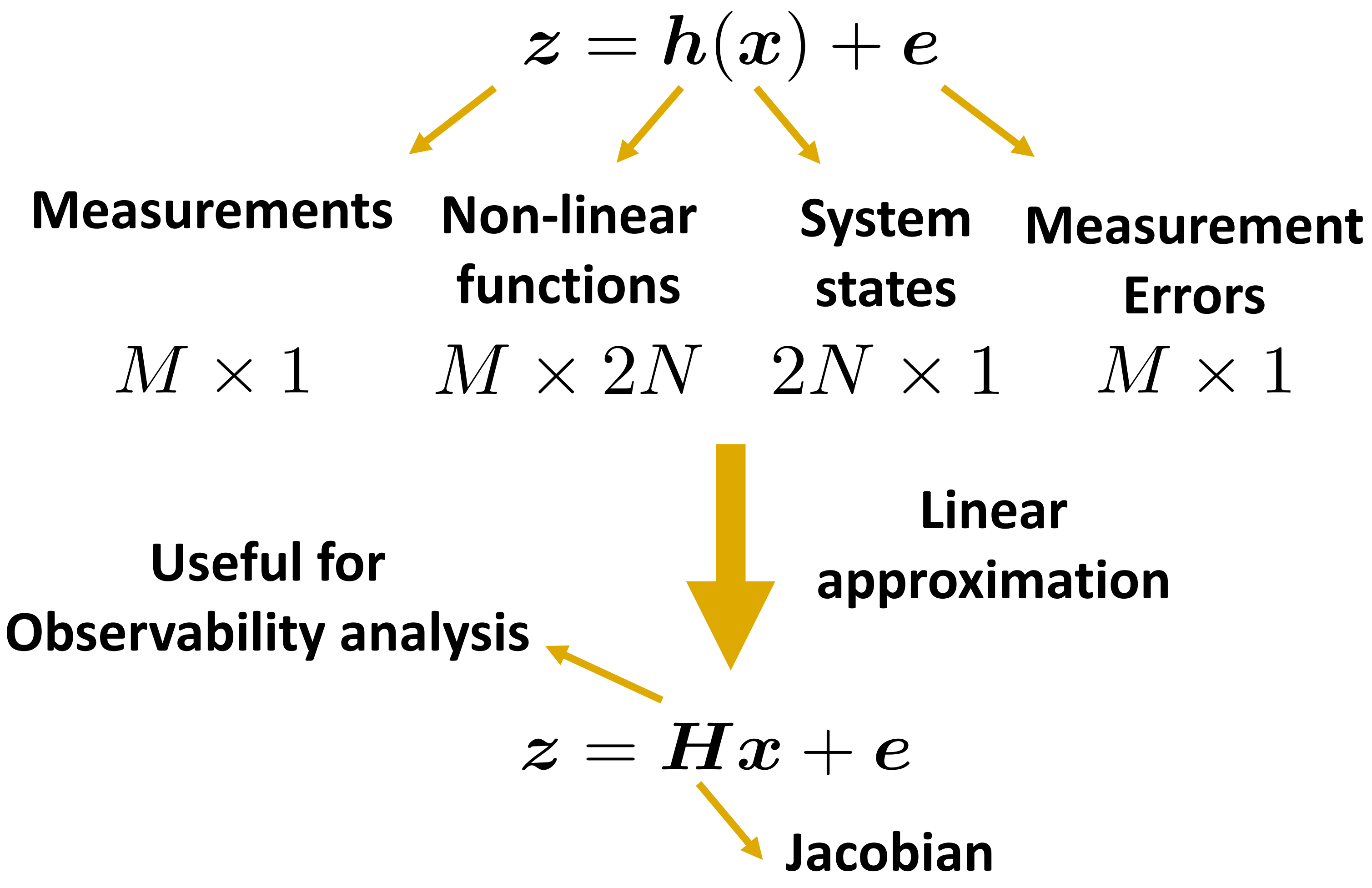
**Scope**

- **Enhance** DSSE performance by including local control logic (droop control)

# State Estimation Preliminaries

## Problem Formulation

- Assuming an *N* bus system (excl. slack bus)



$$\boldsymbol{z} = \boldsymbol{h}(\boldsymbol{x}) + \boldsymbol{e}$$

| Measurements | Non-linear functions | System states | Measurement Errors |
|---|---|---|---|
| $M \times 1$ | $M \times 2N$ | $2N \times 1$ | $M \times 1$ |

**Linear approximation**

**Useful for Observability analysis**

$$\boldsymbol{z} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{e}$$

**Jacobian**

# Conventional DSSE

- DSSE is formulated as an **optimization problem**

**Estimated** **Measured**

**Objective function**

$$min \sum_{i\in\mathcal{M}_P} \frac{(P_i-\hat{P}_i)^2}{\sigma_{P_i}^2} + \sum_{i\in\mathcal{M}_Q} \frac{(Q_i-\hat{Q}_i)^2}{\sigma_{Q_i}^2} + \sum_{i\in\mathcal{M}_V} \frac{(V_i-\hat{V}_i)^2}{\sigma_{V_i}^2}$$

**Measurement accuracy**

**Equality constraints**

$$V_i = f(\boldsymbol{P},\boldsymbol{Q},V_{\text{prev},i}), i\in\mathcal{N}$$

**Recursive non-linear power flow equations [1]**

$$P_i = Q_i = 0, i\in\mathcal{N}_{zero}$$

**Zero Injection buses**

$$P_0 = \sum_{i\in\mathcal{N},i\neq 0} P_i + P_{\text{loss,tot}}$$

**Slack bus active power**

$$Q_0 = \sum_{i\in\mathcal{N},i\neq 0} Q_i + Q_{\text{loss,tot}}$$

**Slack bus reactive power**

[1] G. C. Kryonidis, C. S. Demoulias and G. K. Papagiannis, "A Nearly Decentralized Voltage Regulation Algorithm for Loss Minimization in Radial MV Networks With High DG Penetration," in *IEEE Transactions on Sustainable Energy*, vol. 7, no. 4, pp. 1430-1439, Oct. 2016, doi: 10.1109/TSTE.2016.2556009.

# Proposed Method

**Objective function**

$$min \sum_{i\in\mathcal{M}_P} \frac{(P_i-\hat{P}_i)^2}{\sigma_{P_i}^2} + \sum_{i\in\mathcal{M}_Q} \frac{(Q_i-\hat{Q}_i)^2}{\sigma_{Q_i}^2} + \sum_{i\in\mathcal{M}_V} \frac{(V_i-\hat{V}_i)^2}{\sigma_{V_i}^2}$$

**Equality constraints**

$$V_i = f(\boldsymbol{P}, \boldsymbol{Q}, V_{\text{prev},i}), i \in \mathcal{N}$$

**Recursive non-linear power flow equations**

$$P_i = Q_i = 0, i \in \mathcal{N}_{zero}$$

**Zero Injection buses**

$$P_0 = \sum_{i\in\mathcal{N}, i\neq 0} P_i + P_{\text{loss,tot}}$$

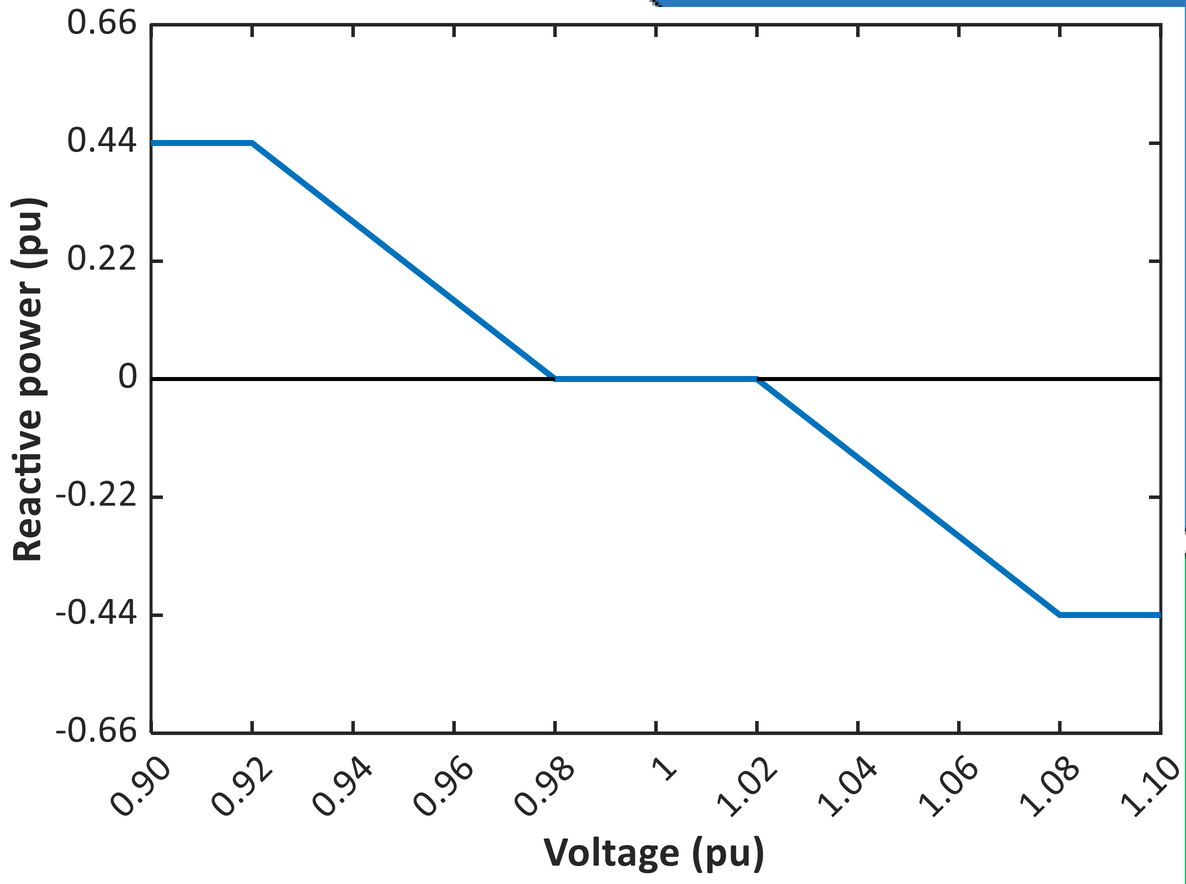
**Slack bus active power**

$$Q_0 = \sum_{i\in\mathcal{N}, i\neq 0} Q_i + Q_{\text{loss,tot}}$$

**Slack bus reactive power**

$$Q_i = g(V_i), i \in \mathcal{N}_{DRES}$$

**Q(V) droop control [2]** →



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[2] IEEE Std 1547-2018, "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003), pp. 1–138, 2018.

# System Under Study

- A radial, 20 kV DS in Greece (16 PVs)

- **Operating scenario**

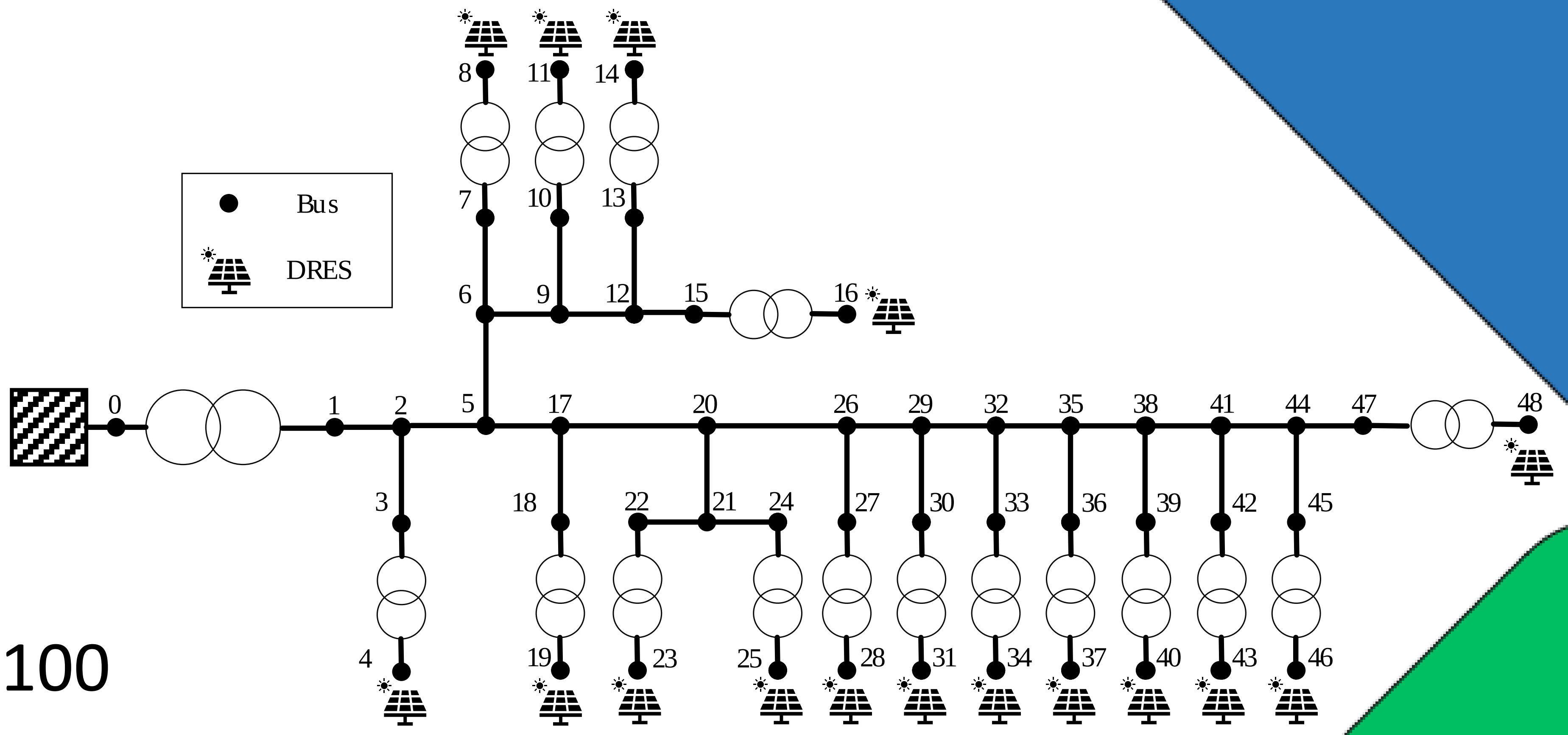
$$Q_{max,i} = 0.44 \cdot S_{r,i}, i \in \mathcal{N}_{DRES}$$

$$P_i^{oper} = \sqrt{S_{r,i}^2 - Q_{max,i}^2}, i \in \mathcal{N}_{DRES}$$

- **Measurements accuracy**

$$\sigma_{P_i} = 0.012 \quad \sigma_{Q_i} = 0.015 \quad \sigma_{V_i} = 0.01$$

- Different measurement errors using 100 **Monte Carlo** simulations



# Impact on Accuracy – Single MC case

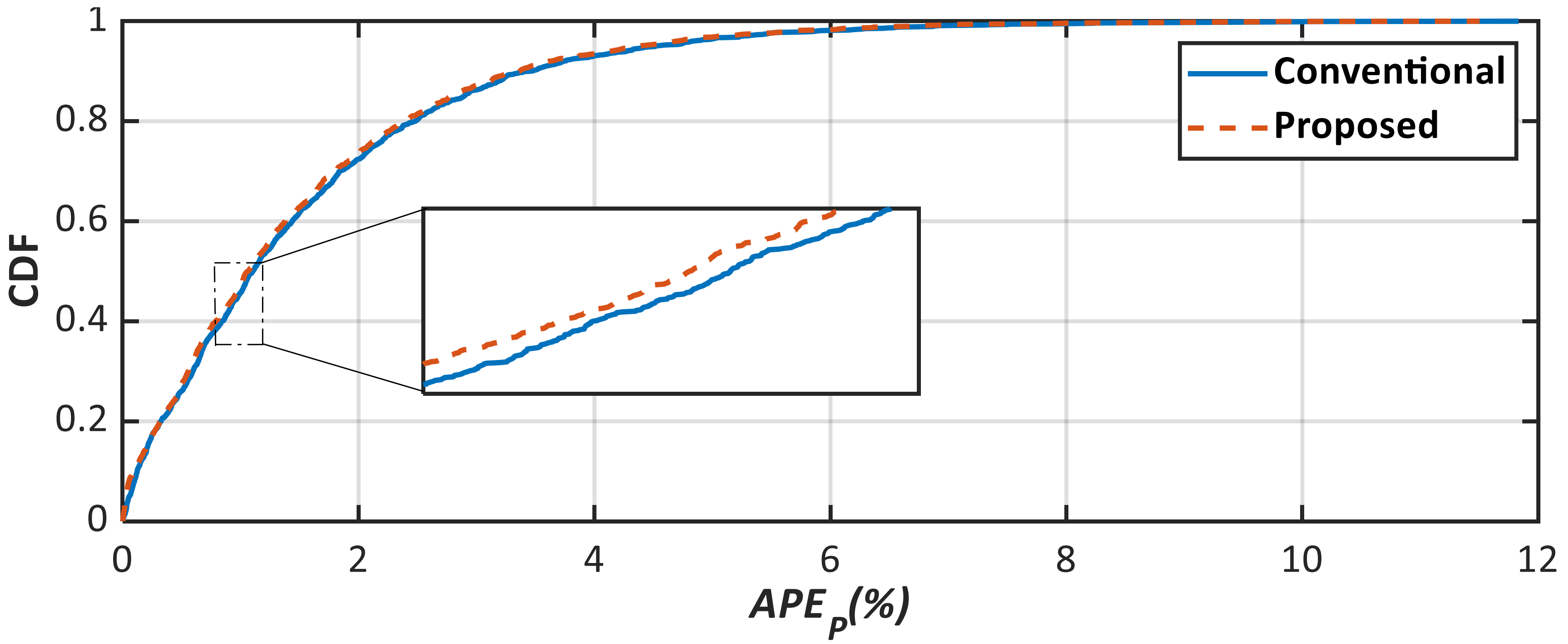
Absolute percentage error (APE) as the main evaluation Index

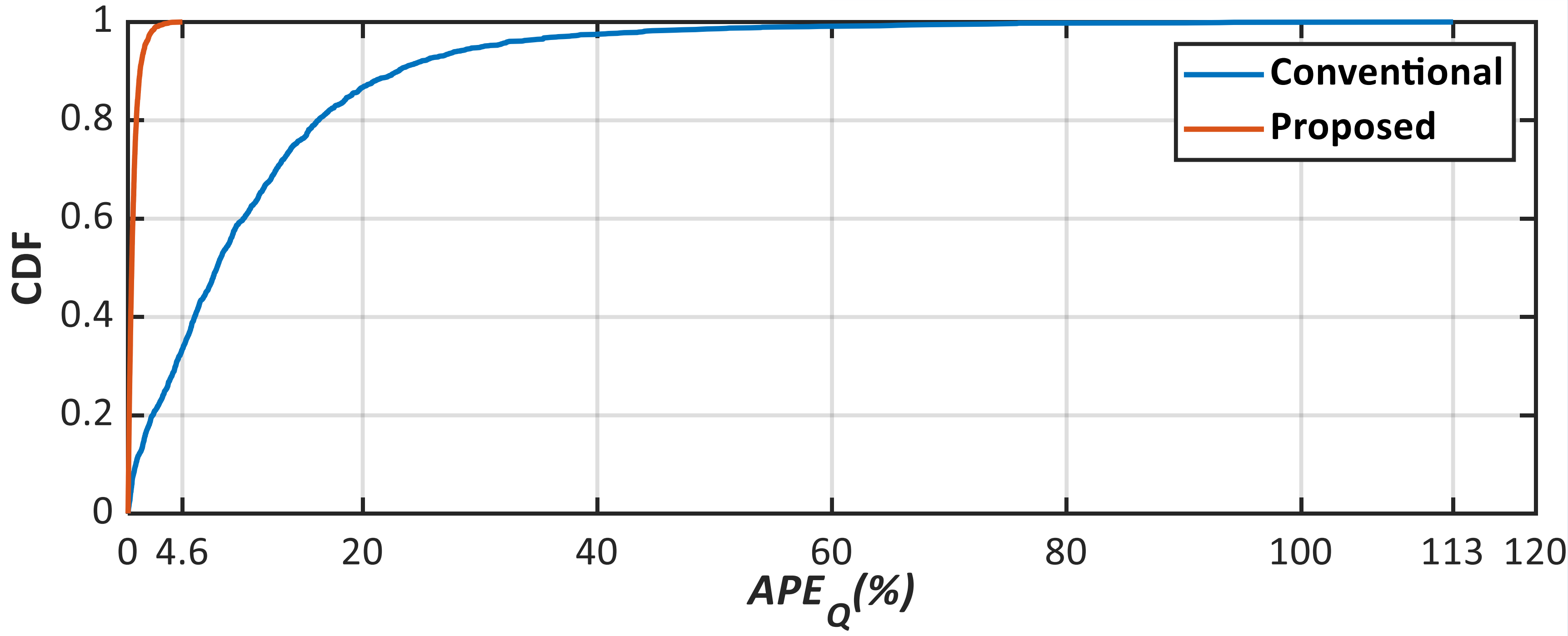
$$\underbrace{APE_{X_i}(\%)}_{P_i,\ Q_i,\ V_i} = \frac{|\overset{\textbf{Estimated}}{X_i} - \overset{\textbf{True value}}{X_i^{true}}|}{X_i^{true}} \cdot 100\%$$

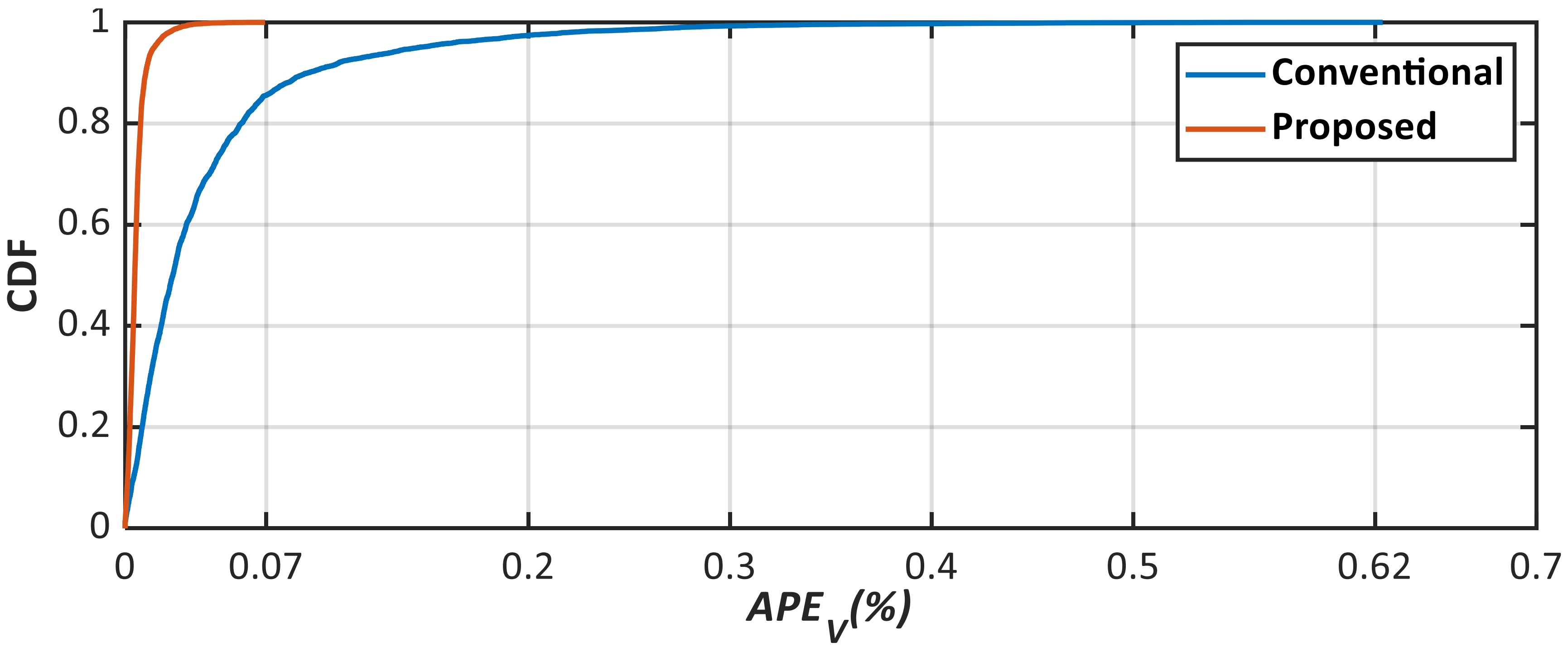
Table 1: Comparison of $APE_{X_i}(\%)$

| | Conventional method | | | Proposed method | | |
|---|---|---|---|---|---|---|
| $i$ | $\boldsymbol{P_i}$ | $\boldsymbol{Q_i}$ | $\boldsymbol{V_i}$ | $\boldsymbol{P_i}$ | $\boldsymbol{Q_i}$ | $\boldsymbol{V_i}$ |
| 4 | 0.42 | 8.69 | 0.015 | 0.4 | 1.04 | 0.0028 |
| 11 | 0.46 | 3.06 | 0.021 | 0.45 | 0.28 | 0.0032 |
| 16 | 0.52 | 4.24 | 0.042 | 0.5 | 0.08 | 0.0077 |
| 23 | 0.75 | 5.76 | 0.057 | 0.73 | 0.01 | 0.0092 |
| 28 | 0.25 | 1.28 | 0.004 | 0.24 | 0.21 | 0.0038 |
| 37 | 1.13 | 8.99 | 0.062 | 1.1 | 0.45 | 0.0011 |
| 43 | 4.9 | 24.83 | 0.297 | 4.76 | 0.99 | 0.0333 |
| 48 | 0.67 | 3.79 | 0.029 | 0.65 | 0.19 | 0.0042 |

# Impact on Accuracy – All MC cases







# Impact on Accuracy – Main Observations

**Conventional method**

- Worst estimates for **reactive power** in conventional method
- This is mainly attributed to the **decreased** measurement accuracy

**Proposed method**

- The proposed method leads to **considerably lower** $APE_{Q_i}$ and $APE_{V_i}$
- The estimation accuracy of active power estimates is **slightly increased**

# Impact on Observability

**Observability criterion :** Full-column rank of matrix $\boldsymbol{H}$

**Conventional method:** $\boldsymbol{H}$

**Proposed method:** $\boldsymbol{H_{aug}} = [\boldsymbol{H}^\top \boldsymbol{H_{droop}}^\top]^\top$

Table 1: Minimum Observability Requirements

| **Method** | Measurements Number | Meter Type |
|---|---|---|
| Conventional | 30 | Power meters |
| Proposed | 15 | Voltage sensors |

**50% less measurements**

# Conclusions

- An **enhanced DSSE** technique is proposed integrating the local control logic of DRESs
- Simulations verified **higher estimation accuracies** for all monitored quantities and especially for **reactive power** and **voltage**
- DS observability **can be ensured** even under limited data resources
- The proposed method could **facilitate** the application of DSSE, allowing for the reliable monitoring of modern, active DSs

# PARTNERS

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VIA VERITAS VITA

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# Thank you!

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